IBTrack: An ICMP Black holes Tracker

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***Abstract*—ICMP is a fundamental part of the Internet as it handles the control and error messages. ICMP's treatment by the network and in particular by different routers it may cross is therefore a key aspect driving troubleshooting and diagnosis processes. In this paper we present IBTrack, a tool that aims at characterizing how the network actually treats different ICMP messages from an user point of view. Specifically, we detail a classification algorithm to categorize router behaviors and we introduce its associated refining method which exploits multiple probing protocols. We illustrate the average Internet router behavior and path composition through results gathered from Planet-Lab nodes using a large CAIDA's snapshot of routed /24. We further show that our refining method improves the routers behavior characterization up to 10% for more than 1% of the total number of observed routers.**

I. Introduction

The Internet Control Message Protocol (ICMP) is one of the main protocols used on Internet and more generally on IPv4 and IPv6 networks. It is responsible for transmitting control and error messages over the network (such as routing control, packet treatment error, etc). Although it operates at the second level of the OSI stacks, it is encapsulated on an IP packet.

An example of the ICMP importance is its key implication in the Path Maximun Transmission Unit Discovery (PMTUD) mechanism [1], [2], [3], which has been developed to avoid IP fragmentation. For instance in IPv4, it sets the *don't fragment* bit (which is not needed in IPv6 since the protocol does not support router fragmentation). If a router cannot transmit the packet because of its size, it must send back to the source an ICMP "Too Big" (type 3 code 4 on IPv4 and type 2 code 0 on IPv6) packet. Iteratively, the source will lower the size of the packet to match the lowest MTU on a path. The importance of a well-chosen PMTU has been discussed in several previous works, and one key aspect to consider from routers perspective is the number of packets per second to handle[4], [5]. In essence, using the highest possible PMTU value results in a significant bandwidth improvement [6] since the packets treatment overhead remains the same regardless of the packet's size. ICMP routing issues can therefore lead to serious connection problems because of their tight links with the PMTU discovery protocol for example.

This motivates our study that aims at analyzing issues related to ICMP packet processing by routers, and in particular so-called "ICMP black holes". The tool presented in this paper, IBTrack, provides users with a thorough analysis of the routers behavior that lie along the path from a source host controlled by the user and any given destination (that is not assumed to be under control). In particular, IBTrack characterizes the routers forging of ICMP error packets and their transport the way back to the source host. It is also important to note that IBTrack should be a "lightweight" tool which only relies on measures performed by the user at the sending host, without requiring any additional resource (i.e. there is no external monitoring and/or vantage point nor any collaboration from the destinations). We further require that IBTrack does not involve any long-term measurement, so it could be used in a timely basis, when a user needs to establish a diagnosis and locate any possible problem origin (similarly to the ping tool).

Let us first compare IBTrack to some related works. In [7], authors describe Reverse traceroute a tool that can be used to perform measurement (using ICMP) at the level of Internet routers back to a specified host. The tool is capable of examining the router-level topology and does not look into the behaviors of routers to forge different types of ICMP packets when needed. Authors of Reverse Traceroute also assume users do have access to multiple vantage points distributed across the Internet. Our approach is similar to the concept explored in [8], where authors propose a system called Hubble which detects IP-level black holes at a global level of IP connectivity. Besides the fact that Hubble needs periodic probing campaigns of the Internet, which IBTrack tries to avoid, our proposed tool aims to further characterize the reasons to which any ICMP -connectivity related issues are due and provides a fine-grained analysis.

The rest of this paper is organized as follows. Section II presents the model used to describe routers and the assumptions made in our work. section III describes the IBTrack algorithms. Section IV focuses on the methodology and tools used for our measurements. Next, section V presents the results from both coarse-grained Internet and fine-grained ISP levels. Finally, section VI concludes the paper.

II. Assumptions and Taxonomy

In this section, we define the terminology used to define the source and destination path components. We also take a closer look at the restrictions implied by IBTrack's main goals and our practical assumptions.

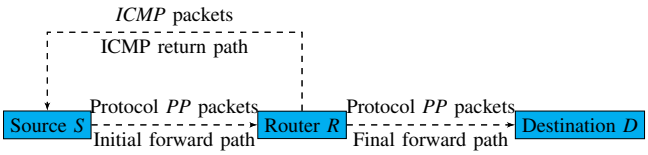

Fig. 1: Paths definitions.

A. Path definitions

Let us consider a path from a source *S* to a destination *D*, and a router *R* along this path (there are typically several routers and *R* is one of them). We assume that the packet flow generated by *S* and destined to *D* uses the probing protocol *PP*. More specifically in this work we consider either `ICMP/IP`, `UDP/IP`, or `TCP/IP`, where `IP` denotes either `IPv4` or `IPv6`. Figure 1 illustrates the following definitions:

- the *initial forward path* is the path between *S* and *R*;
- the *final forward path* is the path between *R* and *D*;
- and the *ICMP return path* is the path taken by `ICMP` packets destined to *S* and either generated by *R* or by a router on the final forward path and that go through *R*;

It is important to note that the initial forward paths and the return `ICMP` paths are not necessarily identical: routers often use different forwarding strategies depending of routing policies. The forward initial or final paths also potentially depend on the nature of *PP*, since routers often use protocol-dependant forwarding rules. Finally, there are potentially as many `ICMP` return paths as the number of routers on the forwarding paths.

B. Assumptions

The algorithms we introduce only take into account the information gathered by the source. The main goal of our approach is to characterize routers behavior along a path in order to help users when troubleshooting connectivity issues that are potentially caused by `ICMP` packets. Therefore we deliberately chose not to rely on external data from vantage point or from the destination during the analysis.

We assume that the routing only depends on the packet's protocol and destination. This is a strong assumption that is however reasonnable in current Internet.

Furthermore, the property used to characterize a router is considered as *global*, independently from the router's IP interface that has been used during the measurement inferring this property. In other words, we assume that all IP interfaces of that router behave identically.

Finally, since we assume we only control the source *S*, it is worth noticing that the only `ICMP` return packet type we can trigger from any router on the network is the Time Exceeded type, which is in theory forged when a packet reaches a router with the `IP` field "Time To Live" equal to zero). During our measurements, will examine `ICMP` return paths only by using `ICMP TTL` packets.

C. Router properties taxonomy

Let us now consider a certain probing protocol *PP* used by the source. For this protocol *PP*, each router along the given path is characterized by the following three key properties:

1) Property P1: "*R* forwards all packets of type *PP* towards *D*".
Said differently, at *R*, each incoming packet on the initial forward path is forwarded on the final forward path. This property, of course, does not imply that these packets reach destination *D*.

2) Property P2: "*R* is cooperative for packets of type *PP*".
In case *R* should send an `ICMP` packet back to the source, either because of an error (e.g. a packet that exceeds the forwarding link MTU) or because the packet asks for a reply (e.g. in case of an `ICMP Echo Request`), then the `ICMP` packet is correctly initialized and sent by *R* on the `ICMP` return path.

3) Property P3: "`ICMP` packets are not filtered by *R*" and by any router on the `ICMP` return path from *R*.
When *R* emits an `ICMP` packet on the return path, this `ICMP` packet is routed all the way back to *S*. This property implies that this `ICMP` packet arrive to *S*, i.e. they are not filtered by any router on the `ICMP` return path from *R*, which is a strong property. In the particular case where the return path contains one or several routers that are also part of the forward path, this property on R implies the same property on these routers.

The router behavior can now be expressed as three logical expressions, one for each property. For instance, for a packet type *P*: `P1.(P2.!P3 + !P2)` means that router *R* forwards these packets and is either cooperative (i.e. sends `ICMP` packets to *S*) but these `ICMP` packets are filtered on the `ICMP` return path, or is non cooperative (i.e. does not generates `ICMP` packets back to *S*).

III. The ICMP black holes tracking (IBTrack) tool

In this section we describe our IBTrack tracking algorithm, whose goal is to refine as much as possible the routers behavior, considering only the initial traffic and the backward `ICMP` path. In a first step, we start by considering a Probing Protocol *PP* and try to determine the router's behavior. Then, in a second step, we explain how IBTrack can sometimes refine the analysis by crossing the results achieved independently with several probing protocols.

A. IBTrack base algorithm

The base algorithm is described in figure 2. At the beginning there is no knowledge at all for router *R*, which corresponds to the state at the top of the graph. In that case each property is "undecided" (i.e. it can be true or false), which is expressed by: `P + !P`.

Then the algorithm is composed of two main steps:

- test the forwarding path through *R*;
- test the `ICMP` return path from *R*;

We now detail these two steps:

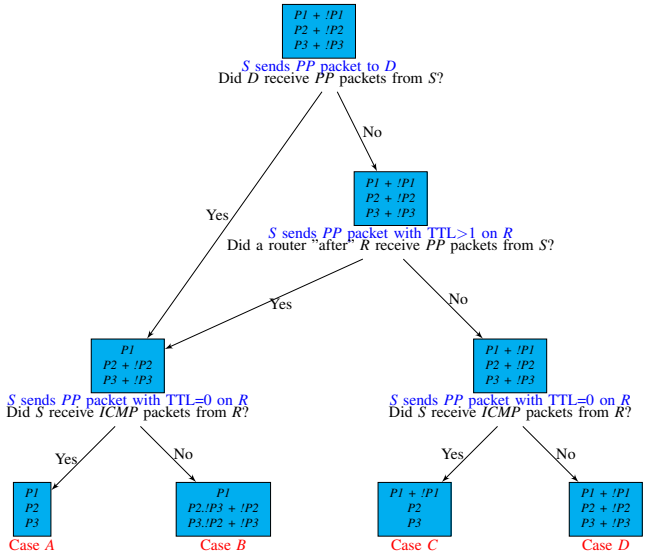

Fig. 2: Base algorithm for router's behavior characterization

1) Forwarding path through R: We first want to test the `P1` property (forwarding property towards *D*). It can be verified in two ways: either the destination replied, which implies that it has received an incoming packet, or we can assert that a router on the final forward path received an incoming packet. This second method is typical of situations where source *S* received `ICMP` packets from a router on the final forward path (i.e. after router *R*).

2) ICMP return path from R: We now want to check the `P2` and `P3` properties. For the `P2` property we must verify that the router forges the `ICMP` error packet and emits it on the `ICMP` return path. This could be tested by monitoring the `ICMP` return path. Nevertheless, as we do not control any router of the `ICMP` return path, we only rely on the reception by the source of the `ICMP` error packet. For the `P3` property, since it concerns the `ICMP` return path itself, it can only be evaluated with the reception of `ICMP` error packets by the source.

3) Classification details: We now present the result of this classification, which consists in four cases, depending on the properties that could be verified or not.

a) Case A: `P1.P2.P3`

This is the "ideal" router which forwards the initial packets and forges `ICMP` error packets that all arrive to the source.

b) Case B: `P1.(P2.!P3 + !P2).(P3.!P2 + P3)`

`P1` is verified, but the interesting part of this case comes from the `P2` property. In this case, the router forwarded the initial packets and also dealt with them (i.e. filtering and packet processing). However the source did not receive any `ICMP` error packet whereas such a packet should have been forged since the source *S* sent a packet whose TTL ("Hop Count" in case of `IPv6`) has been decremented to 0 by *R*). It leads to two possibilities:

- `P2` $\Rightarrow$ `!P3`: the `ICMP` error packet is forged but is blocked along the `ICMP` return path.
- `P3` $\Rightarrow$ `!P2`: the `ICMP` return path forwards `ICMP` packets correctly, however the router *R* did not not forged any such packet.

c) Case C: `(P1 + !P1).P2.P3`

The source gets the `ICMP` error from the router, but we have no clue that a router on the final forward path received any initial packet.

d) Case D: `(P1 + !P1).(P2 + !P2).(P3 + !P3)`

For these type of routers, we cannot infer anything because the source did not get back any data.

This base algorithm is applied to every routers in a path (defined by its source and destination) for protocol *PP*, by increasing the TTL value It results in a collection of cases (*A*, *B*, *C* or *D*) for each router along the forward path.

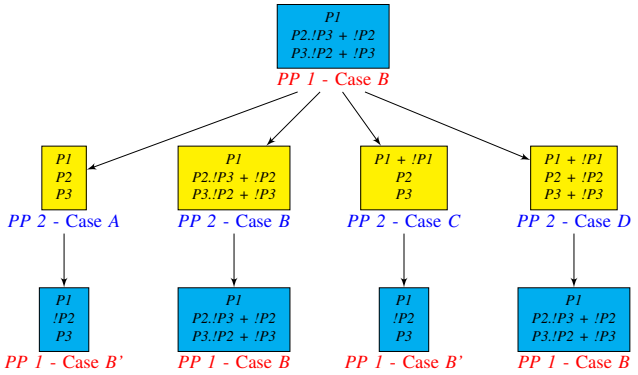

Fig. 3: Refining case *B* with another probing protocol

B. IBTrack refining algorithm

Let us now explain how we can refine the previous algorithm that depends on the probing protocol *PP* that has been used for probing the network. Let us first notice that the `P3` property concerns exclusively the `ICMP` return path which is the same independently from the probing protocol *PP* [1]. Thus, for a given router *R*, we can use the deductions made on the `P3` property using a probing protocol *PP1* to refine the deductions made using another probing protocol *PP2*. This is the key idea of our refining algorithm. However, in order to be able to apply this refinement, we must first identify the same router for both probing protocols, whereas we do not necessarily have its identity (it can be a wildcats "*" in a `traceroute` trace). This aspect is addressed in section IV-C, and for the moment we assume that this assertion as true.

The combination of the results of the algorithm for two distinct probing protocols is detailed in figures 3 and 4, for router *R*. Since we can only use deductions for the `P3` property, cases *A* or *C* cannot be refined (property `P3` is already known in that case). Therefore we focus on cases *B* and *D*.

[1]This is a direct consequence of our assumption that routing only depends on the protocol along the return path, here ICMP, and the destination (here *S*).

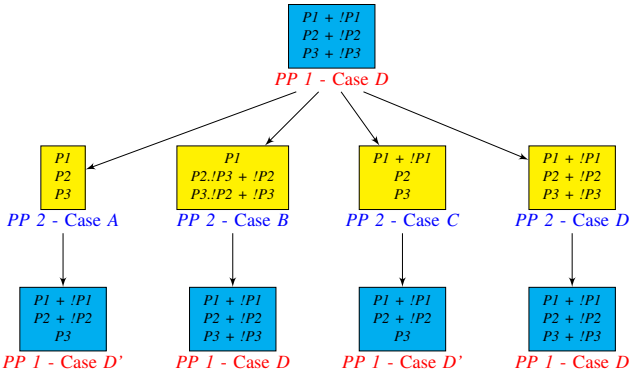

Fig. 4: Refining case *D* with another probing protocol

ICMP	UDP
15 213.248.90.250	15 213.248.90.250
16 *	16 *
17 205.171.11.98	17 205.171.11.98

(a) two *B* cases

ICMP	UDP
6 195.83.166.161	6 195.83.166.161
7 193.51.181.222	7 *
8 193.51.189.202	8 193.51.189.202

(b) *A* case and *B* case

Fig. 5: Two examples of multiple probing protocol results

1) Initial case B for probing protocol PP1 (Fig.3): This is the most interesting case. When property `P3` is verified with the second probing protocol, *PP2*, from the second conditional we can deduce that `P3` $\Rightarrow$ `!P2`. Thus, if probing with protocol *PP2* ends in cases *A* or *C*, we can conclude that the `P3` property is verified for protocol *PP1*, which implies that `P2` is not. This creates a subcase for *B* that we call *B'*: `P1+!P2+P3`.

2) Initial case D for probing protocol PP1 (Fig.4): This case can only be refined on the `P3` property itself since there is no material implication or link with another property. This only happens when we end in cases *A* or *C* with the second probing protocol.

3) Refining using multiple probing protocols: It is of course possible to use more than one probing protocol to refine the results obtained with *PP1*. Nevertheless, for this to be true, we must assert that the paths are the same for every combination of the probing protocol and of the refining protocol in order to consider that `P3` property is common.

C. Examples

Figure 5 illustrates the refining algorithm through two examples extracted from our experiments.

In the `traceroute` outputs of figure 5a, the 16^{th} router is a *B* case for both protocols since: (i) it forwards the initial protocol (the 17^{th} router replied which implies that it has received at least one initial packet); but (ii) no `ICMP` return packet is received by the source. There is no refining possible in this case and: `P1.(P2.!P3 + !P2).(P3.!P2 + P3)`

In the `traceroutes` outputs of figure 5b), the 7^{th} router is a *B* case for `UDP` probing whereas it is an *A* case for `ICMP` probing (the `ICMP` return packet is received by the source). As the `ICMP` return path is the same (source, protocol and destination are identical), we deduce that for `UDP` packet the router does not forge the `ICMP` return packets. The categorization for `UDP` probing is therefore refined to the *B'* case: `P1+!P2+P3`

The formal model and algorithms being described, the next section will focus on the methodology and on the tools used for Internet measurements.

IV. Measurement Methodology

Before describing the tools and methodology used during the measurements, we detail how we chose the `IP` addresses to probe.

A. Selection of destination's IP

To probe a meaningful set of Internet, we used a CAIDA[9] snapshot of the routed `/24 IPv4`. This snapshot is composed of a part of the routed `/24` (approximately 10,000) and gives for each a random IP in the `/24`. It is important to notice that there is not necessarily a running host behind each `IP` in the snapshot.

B. Tools

To perform probing, we used `scamper`[10] that implements, among others, the `paris-traceroute`[11] functionnality over the Planet-Lab[12] nodes.

1) Paris-traceroute: This is an improved version of the classical `traceroute` tool. In particular this tool reveals more routers and links over the path explored and removes some false links inferred by the usual `traceroute`. This is therefore highly benefic to our needs.

2) Planet-Lab: This is a world wide network aiming to help academic and industrial researchers focusing on new network services. In our test, it provides multiple servers across the world that we use to probe the same destination set of `IP` addresses. Therefore it helps us improving the coverage of the possible paths to the selected set of `IP` addresses.

3) Scamper: This is a program that implements most of the classical Internet measurement tools (like `ping` or `paris-traceroute`) that can be launched to run in parallel. In particular it is developed to run on Planet-Lab nodes.

One of the features of `scamper` we use is that after five unidentified routers (i.e. not responding, thus appearing as "*" in the `traceroute` output) it stops. Figure 6c shows a `traceroute` terminating like this. This situation can result from different causes, like for instance a single router filtering packets, or multiple routers not replying. Nevertheless, we will deliberately take into account only the first "*" during our tests.

Protocol 1	Protocol 2	Protocol 1	Protocol 2
1 R1	1 R1	1 R1	1 R1
2 *	2 R2	2 *	2 R2
3 *	3 R3	3 *	3 R3
4 *	4 R4	4 R4	4 *
5 *	5 R5	5 R5	5 *
6 R6	6 R6	6 R6	6 R6

(a) Two pairs of traceroute outputs considered as the same path

Protocol 1	Protocol 2
1 R1	1 R1
2 R21	2 R22
3 *	3 R3
4 R41	4 R42
5 *	5 R5
6 R6	6 R6

(b) Two traceroute outputs considered as the same path when allowing two different routers

ICMP
12 198.108.23.21
13 *
14 *
15 *
16 *
17 *

(c) Example of a traceroute finishing with five unidentified routers

Fig. 6: Examples of the path matching algorithm and scamper output

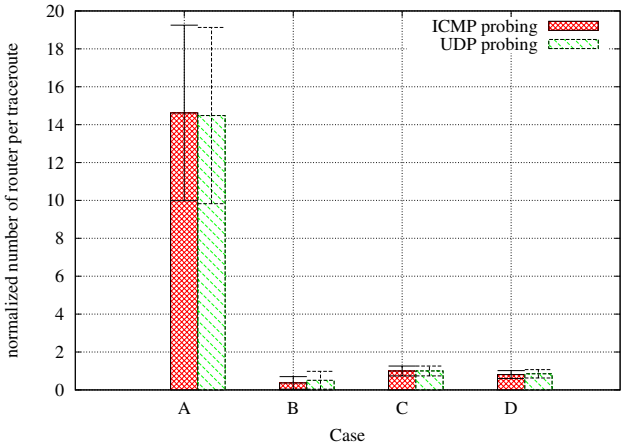

Fig. 7: Normalized (per traceroute) number of routers per case (with standard deviation)

C. Identifying common path

One of the main challenges before applying the refining algorithm which uses multiple probing protocols is to be able to match paths that seem to be different. In principle the presence of an unidentified router on a path (i.e. a "*" in the `traceroute` output) prevents path matching for the final forwarding path. But this situation must be improved. Indeed, if the router has to be identified to allow the application of our refining algorithm, then we would only perform refining between *A* and *C* cases, which is of little interesting because these cases already share the same state for the property `P3`.

1) Handling unknow routers: The first and straightforward assumption we make consists in ignoring unknown routers from a path when matching two paths with the same source and destination but with different probing protocols.

Formally, there is no proof for this assumption, but we are convinced that given the maximum number of consecutive unknown routers we allowed (5 before `traceroute` halts) for a protocol, if two paths share the same number of routers and if the identified routers are the same, then the two paths are most likely the same.

For instance, figure 6a exhibits two situations considered as belonging to the same path by the path matching algorithm.

2) Handling tunnels: We also wanted to add to the path matching algorithm the capability to identify tunnels. More particularly, we want to isolate path divergences due to *per-flow* routing (for example through `MPLS` tunnel[13]).
Therefore, we improved our algorithm by allowing some consecutive identified routers to be different on the same path. This feature adds itself to the previous one; thus "consecutive identified routers" do not involve potential unknown routers. Nevertheless, the number of routers and their position on the path must remain the same.

Figure 6b illustrates two paths being considered as identical by the path matching algorithm when allowing two different consecutive identified routers.

The following section presents large scale measurements gathered from Planet-Lab nodes and a fine-grained analysis of the algorithm results.

V. Measurement results

We first detail the results obtained from 30 Planet-Lab nodes to a set of CAIDA's routed `/24` composed of more than 10,000 `IP` addresses. Then we detail the results obtained from a typical ISP user probing the same set of `IP` addresses, using `ICMP`, `UDP`, but also `TCP`.

A. Coarse-grain Internet results

1) Paths characterization: figure 7 represents the normalized number of router per case. On average, a `traceroute` is composed of 16.78 routers distributed as followed:

- *A* case - 14.5 routers
- *B* case - 0.45 router
- *C* case - 1 router
- *D* case - 0.83 router

Figure 8 shows the distribution of cases depending on the distance between the router and the initial source. Note that when handling a "premature end" of a `traceroute` (i.e. when finishing with five "*"), the *D* cases are only counted once (it corresponds to the closest router from the source) as explained in section IV-B3.

This figure shows that the closer a router is to the source, `S`, the mostly it will be of case *A*. On the opposite, the further a router is, the highest the probability to fall in *C* and *D* cases, which in turn comes at the expense of a lower probability of the router would be in case *A*. Perhaps not surprisingly, this shows that the longer the path is the higher the chances the routers would behave according to the *D* unexplicative case.

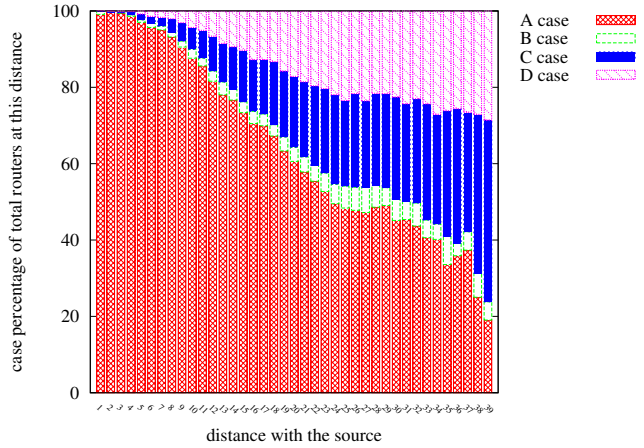

Fig. 8: Case percentage with regards to the distance to the source S

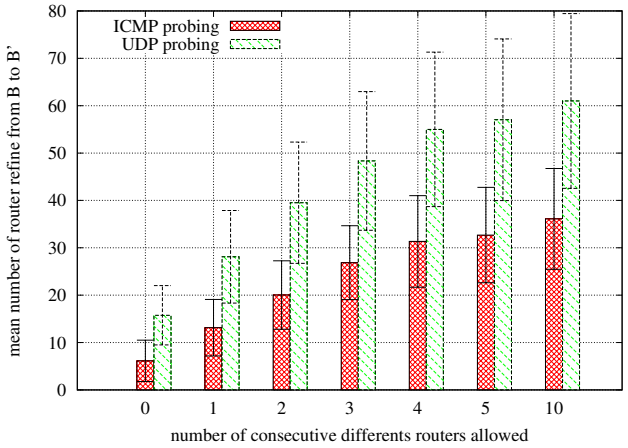

Fig. 10: Mean number of router refined from *B* to *B'* case depending of the path matching algorithm configuration (with standard deviation)

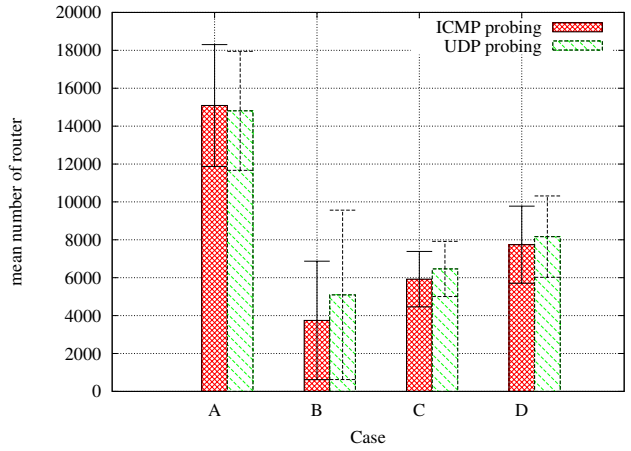

Fig. 9: Mean number of routers per case (with standard deviation)

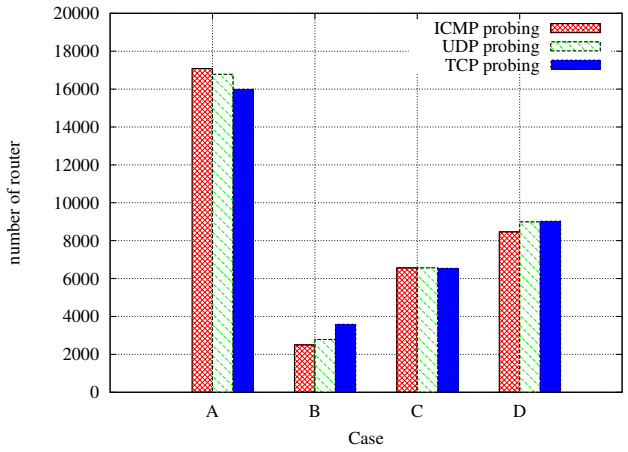

Fig. 11: Number of routers per case with 3 probing protocols

2) Routers characterization: figure 9 summarizes the classification of routers encountered during the probing of every IP of our destination set, from each Planet-Lab nodes, using the ICMP and UDP protocols. We remind that for the *D* case, results are divided by 5 due to the "premature end" of a traceroute (section IV-B3). In opposition to the two previous figures, we add that the router seen are counted only once as we want to survey the Internet's average router behavior (previously we were focusing on the path instead).

Figure 10 details the results of the refining algorithm applied to the Planet-Lab outputs. We first configured the path comparison algorithm to perform an exact path matching and then changed it to allow a certain number of different routers along the path. With a strict path matching configuration, we refine 0.16% (ICMP) and 0.31% (UDP) of the *B* case. This ratio grows up to 0.87% (ICMP) and 1.12% (UDP) when allowing up to five different consecutive identified routers. This measure (particularly the small difference when allowing five or ten different routers) can be associated to the fact that more than 90% of MPLS tunnels (which are present in at least 30% of Internet's traceroute) are at most five hops long[13].

B. Fine-grain results

Let us now consider the results obtained by a single user using a single host, connected through a given ISP. The set of IP addresses is the same, and we use the ICMP, UDP, but also TCP probing protocols.

Figure 11 presents the results of the classification algorithm applied on the three probing protocolsICMP, UDP and TCP. Although the general distribution is globally the same, there are more *A* cases and fewer *B* cases than with Planet-Lab results (figure 9).

Figure 12 details the refining algorithm used for TCP, which refines TCP results either using ICMP solely, or UDP, or both probing protocols. It illustrates well the fact that, when using multiple probing protocols to refine a single other protocol-based properties output, the results are lower

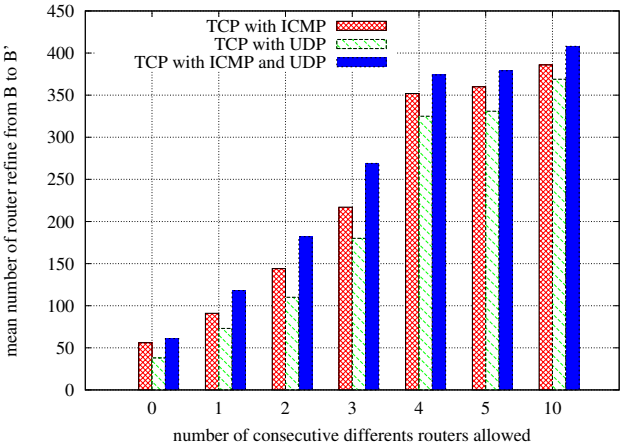

Fig. 12: Refining of TCP probing protocol *B* case

than what could be expected from the sum of the refining using single protocols outputs, as explained in section III-B3. Indeed, we observe that the improvement of the refining algorithm while using two protocols to refine a single one is small. For instance, when allowing five different consecutive identified routers, the improvement is: 5.2% when comparing `ICMP` to `ICMP+UDP`, and 14.5% between `UDP` and `ICMP+UDP`. We interpret this at a router level by bearing that there is an explicit policy on these routers that forbids it to forge `ICMP Time Exceeded` packets when the initial protocol is `TCP`.

Nevertheless, when using both `ICMP` and `UDP` to refine the *B* case of `TCP`, we see that we are able to completely specify the behavior of 10% of the routers encountered. Globally, we manage to refine the classification of 1% of the routers seen.

VI. Conclusion

This work has investigated the problem of `ICMP` black holes tracking. Our contributions are fourfold: we first introduced a taxonomy for router properties, regarding `ICMP`. We have shown that three fundamental properties are sufficient to classify Internet routers with respect to the `ICMP` protocol processing.

Secondly we have introduced a methodology to classify the routers of a path, using a given probing protocol, into four cases. These cases represent the possible logical relationships between the three fundamental properties. Then we introduced a refinement procedure, using two or more probing protocols, that enables to better classify the routers. This approach does not require any control from within the Internet or at destination. It can therefore be immediately ported to any operating system and used by any user.

Third, we designed the IBTrack tool that implements the above algorithm.

Fourth, we performed several large scale experiments to analyze our tool and methodology in real conditions. In these experiments, we also report several insights on the Internet routers `ICMP` processing.

We therefore believe that this work is a significant step forward. In particular it will help many network administrators to better understand `traceroute` outputs and debug complex `ICMP` related problems within routers.

This work deliberately makes very minimalist assumptions on what users might control while processing and diagnosing network failures messages (only the source is controlled). As such, the proposed approach can be easily extended by relaxing some constraints (e.g. the user also controls the destination) or by revisiting some of our assumptions on network functionalities (e.g. the presence of vantage points).

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